OPEN CHARM PRODUCTION IN BINARY REACTIONS WITHIN THE REGGE THEORY

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We analyze the open charm production in the binary $\pi\, p \to \bar{D}\, \Lambda_c$ and $\pi(\rho)\, J/\psi$ reactions within the Regge theory including the absorption corrections. The calculations show that the total cross section is about a few μb for the first processes and a few mb for the second reactions at energy close to the threshold. Then it decreases with increasing energy according to the true Regge asymptotics.

In the last decade the problem of searching for a quark–gluon plasma (QGP) has been rising in line with the development of new experimental facilities [1]. For instance, the J/ψ-meson plays a key role in the context of a phase transition to the QGP where charmonium ($c\bar{c}$) states should no longer be formed due to color screening. However, the suppression of the J/ψ and ψ' mesons in the high-density phase of nucleus–nucleus collisions might also be attributed to inelastic comover scattering, (see, for example, [2,3] and references therein) provided that the corresponding J/ψ-hadron cross sections are in the order of a few mb [4,5,6]. Present theoretical estimates differ by more than an order of magnitude, especially with respect to J/ψ-meson scattering, so that the question of charmonium suppression is not yet settled. Moreover, the calculation of these cross sections within the chiral Lagrangian approach results in their constant or slowly increasing energy dependence [4,5,6], which contradicts the true Regge asymptotics predicting the decreasing one when the energy increases. The inclusion of the meson structure and the introduction of the meson form factors in this Lagrangian model leads to a big uncertainty for the shape and magnitude of the J/ψ breakup cross sections by mesons.

The amplitude of the reaction in question has to satisfy the Regge asymptotics at large s. In Refs. [7,8] the cross section of the reaction $\pi\, N \to \bar{D}(\bar{D}^*)\, \Lambda_c$ was estimated within the framework of the Quark–Gluon String Model (QGSM) developed in Ref. [9]. The QGSM is a nonperturbative approach based on the ideas of a topological $1/N$ expansion in QCD and on the Regge theory.

We apply such an approach to the analysis of the processes like $\pi N \to \bar{D}\,\Lambda_c(\Sigma_c)$ and $\pi(\rho)\,J/\psi \to \bar{D}D^*(\bar{D}^*D^*, \bar{D}D)$. The amplitude for such reactions corresponding to the planar graph with u and $\bar{c}$ quark exchange in the t channel can be written as (see Ref. [7] and [8])

$$\mathcal{M}(s,t) \;=\; C_I\, g_0^2\, F(t)\,(s/s_0)^{\alpha_{u\bar{c}}(t)-1}\,(s/\bar{s})\ , \tag{1}$$

where $g_0^2/4\pi = 2.7$ is determined from the width of the ρ-meson [7]; the isotopic factor $C_I = \sqrt{2}$ for the $\pi^\pm\, N$, $\pi(\rho)^\pm\, J/\psi$ reactions and $C_I = 1$ for the $\pi^0\, N$, $\pi^0(\rho^0)\, J/\psi$ reactions; $\alpha_{u\bar{c}}(t) = \alpha_{D^*}(t)$ is the D^* Regge trajectory, $\bar{s} = 1$ GeV^2 is a universal dimensional factor, $s_0 = 4.0$ GeV^2 is the flavor dependent scale factor which is determined by the mean transverse mass and the average-momentum fraction of quarks in colliding hadrons [7], and $F(t)$ is the form factor describing the t dependence of the residue. We assume, as in Refs. [7,8], that the D^* Regge trajectory is linear and therefore can be expanded over the transfer t

$$\alpha_{D^*}(t) \;=\; \alpha_{D^*}(0) \;+\; \alpha'_{D^*}(0)\,t\ , \tag{2}$$

where the intercept $\alpha_{D^*}(0) = -0.86$ and its derivative $\alpha'_{D^*}(0) = 0.5$ GeV^{-2} are found from their relations to the same quantities for the J/ψ and ρ trajectories which are known, see Ref. [7]. The form factor $F(t)$ was presented in Ref. [7] as

$$F(t) \;=\; \Gamma(1-\alpha_{D^*}(t))\ , \tag{3}$$

where $\Gamma(x)$ is the Gamma–function. Note, that in the region of negative t for the reactions $\pi N \to \bar{D}\,\Lambda_c(\Sigma_c)$ $F(t)$ exhibits a fractial growth (which is faster than exponential) and therefore is not acceptable. For this type of reactions we will use the conventional parameterization [7,8]

$$F(t) \;=\; \Gamma(1-\alpha_{D^*}(0))\ . \tag{4}$$

As is shown in Ref. [11], at intermediate energies the absorption corrections due to the elastic and inelastic rescattering of final hadrons produced in binary reactions can be very sizable. They can greatly reduce the magnitude of the cross section especially at energies close to the threshold. This is why we have to include these effects. We estimate these absorption corrections using the standard method of reggeon calculus and the quasieikonal approximation. The amplitude of a binary reaction in the impact parameter space is represented as [11]

$$\mathcal{M}(s,b) \;=\; \mathcal{M}_R(s,b)\,\exp\left(-\chi(s,b)\right)\ , \tag{5}$$

where $\mathcal{M}_R(s,b)$ is the b-space representation of the simple Regge-pole exchange amplitude

$$\mathcal{M}_R(s,b) \;=\; \int \frac{d^2\mathbf{q}_\perp}{2\pi}\, \mathcal{M}_R(s,\mathbf{q}_\perp^2)\, \exp\left(i\mathbf{b}\mathbf{q}_\perp\right) \tag{6}$$

and the amplitude $\mathcal{M}_R(s,\mathbf{q}_\perp^2)$ in our case is given by Eq. (1). The function $\chi(s,b)$ in Eq. (5) includes the possible elastic and inelastic rescatterings of the final charmed mesons. The elastic $\bar{D}\,\Lambda_c$ or $\bar{D}D^*$ scattering is determined mainly by the one-Pomeron exchange graph at $s > s_{\rm thr}$, therefore [11]

$$\chi(s,b) \;=\; \frac{C\,\sigma^{\rm tot}}{4\pi\Lambda(s)}\, \exp\left(-\frac{b^2}{2\Lambda(s)}\right)\;, \tag{7}$$

where $\sigma^{\rm tot}$ is the total cross section of the interaction of final $\bar{D}\,\Lambda_c$ or $D(D^*)$ mesons; $\Lambda(s)$ is the slope of the differential cross section of $D\,\Lambda_c$ or $D^*\bar{D}(D^*\bar{D}^*, D\bar{D})$ elastic scattering. For the one-Pomeron exchange graph

$$\Lambda_{\mathcal{P}}(s) \;=\; 2\alpha'_{\mathcal{P}}(0)\,\ln(s/s_0) \tag{8}$$

where $\alpha'_{\mathcal{P}}(0) \simeq 0.2\ ({\rm GeV}/c)^{-2}$ is the slope of the Pomeron trajectory. Returning from the b-representation of the scattering amplitude, given by Eq. (5), to the momentum space we can calculate the $\mathcal{M}(s,t)$ including the absorption corrections. Finally, instead of Eq. (1) we have the following form of the scattering amplitude including the absorption corrections

$$\begin{aligned}\mathcal{M}(s,t) \;=\; & C_I\, g_0^2\, F(0)\, \frac{(s/s_0)^{\alpha_{\mathcal{D}^*}(0)-1}\,(s/\bar{s})}{\Lambda_{\mathcal{D}^*}(s)} \left(\frac{s}{s_0}\right)^{\alpha'_{\mathcal{D}^*}(0)(q_0^2-q_z^2)} \\ & \times \int_0^\infty f_{\mathcal{D}^*}(s,b)\, C_A(s)^{f_{\mathcal{P}}(s,b)}\, j_0(bq_\perp)\, bdb\;,\end{aligned} \tag{9}$$

where $t = q^2 = q_0^2 - q_z^2 - q_\perp^2$, $j_0(x)$ is the Bessel function of the zero order, $C_A(s) = \exp\left(-\chi(s,0)\right)$ and $f_R(b) = \exp(-b^2/(2\Lambda_R(s)))$. The "enhancement factor" $C \simeq 1.5$ has been found in Ref. [12] and [11] to be in good agreement with the experiment for elastic $\pi p, Kp, \bar{p}p$ scatterings. So, in our calculations we have taken the same value for C entering the Eq. (7). The values for the total cross section of the scattering of final D-mesons can be calculated at $s > s_{\rm thr}$ within the one-Pomeron (secondary Reggeons) exchange graphs and with some estimates of the D-meson radius from [13], it is $\sigma^{\rm tot}_{D\bar{D}^*} \simeq 10 \div 12$ mb, and we assume that $\sigma^{\rm tot}_{D\Lambda_c} \simeq 3/2\,\sigma_{D\bar{D}^*}$.

The differential cross section for the discussed reactions is then

$$\frac{d\sigma}{dt} \;=\; \frac{1}{64\pi s\, p_{\rm c.m.}^2} \sum_{\rm isospin} |\mathcal{M}(s,t)|^2\;, \tag{10}$$

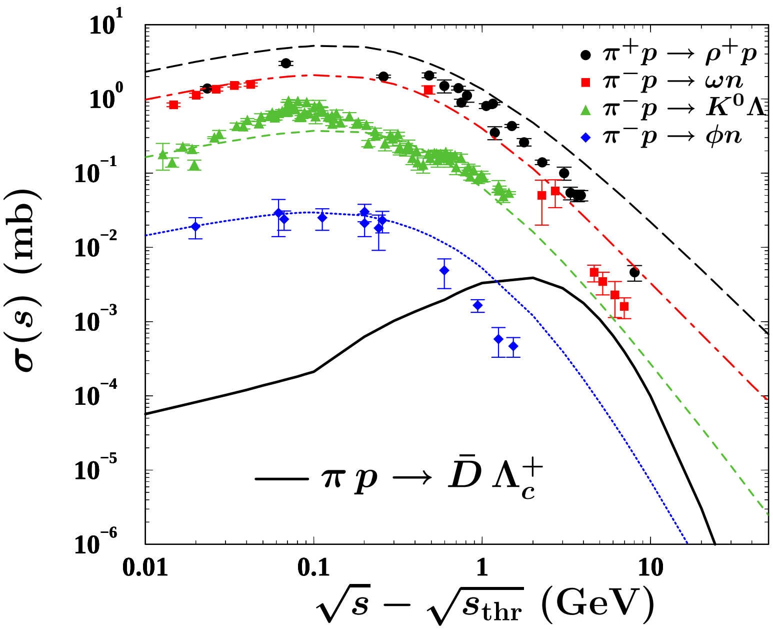

Figure 1. The experimental cross sections for the reactions $\pi^+ p \to \rho^+ p$, $\pi^- p \to \omega n$, $\pi^- p \to K^0 \Lambda$ and $\pi^- p \to \phi n$ from Ref. [15] and the theoretical calculations, see the text. The lower solid line is the prediction for the process $\pi\, p \to \bar{D}\, \Lambda_c^+$ within the Regge theory.

where $p_{\rm c.m.}$ is the initial momentum in the c.m.s. The total cross section of the process discussed is calculated as the integral of Eq. (10) over t.

In Fig. 1 the total cross section of $\pi\, p \to \bar{D}\, \Lambda_c$ reactions as a function of $\sqrt{s} - \sqrt{s_{\rm thr}}$ is presented, here $\sqrt{s_{\rm thr}}$ is the threshold energy in the c.m.s. The experimental data on $\pi\, N \to \rho(\omega, \phi)$ and $\pi^-\, p \to K^0\, \Lambda^0$ are presented to illustrate their enhancement at the energy close to the threshold, similarly to the one in the process discussed. The theoretical calculations of the cross sections have been done within the Regge theory including the suppression of the open (K, Λ) and hidden (ϕ) strangeness production in comparison to the $\rho(\omega)$ one in the inclusive $\pi\, p$ reactions at $z \to 1$, where z is the momentum fraction of the produced hadron.

In Figs. 2,3 the energy dependence of the cross section of D-meson production in binary $\pi(\rho)\, J/\psi$ reactions is presented. It is seen from Figs. 2,3 that the maximum values of these cross sections at $s > s_{\rm thr}$ are a few mb. Contrary to the results obtained within the Lagrangian model [4,5,6], all these cross sections and the ones for $\pi\, p \to \bar{D}\, \Lambda_c(\Sigma_c)$ processes decrease when s increases according to the true Regge asymptotics.

Note, that the absorption corrections decrease the magnitude of the

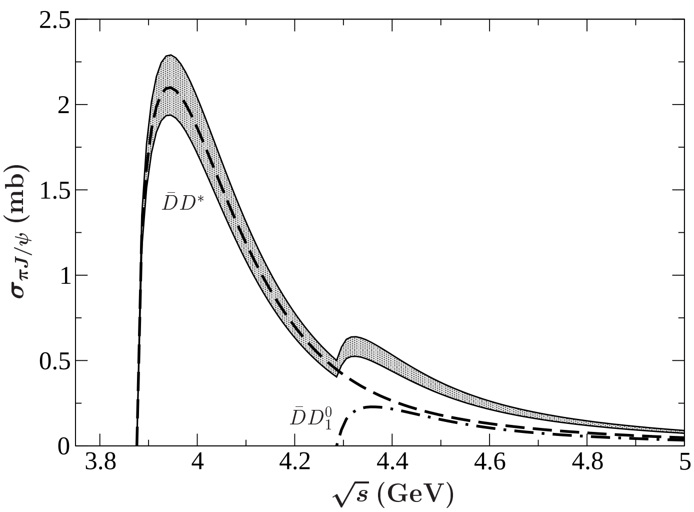

Figure 2. The energy dependence of the total $\pi J/\psi$ cross sections in the Regge model including the absorption corrections. The figure shows also all significant partial cross sections open to $\sqrt{s} = 5$ GeV. The total cross section includes charge conjugation final states where appropriate. The estimated range of uncertainty, due to parameter variation, is shown as a shaded band.

cross sections discussed greatly at energies close to the threshold and can be neglected at large s.

Acknowledgments

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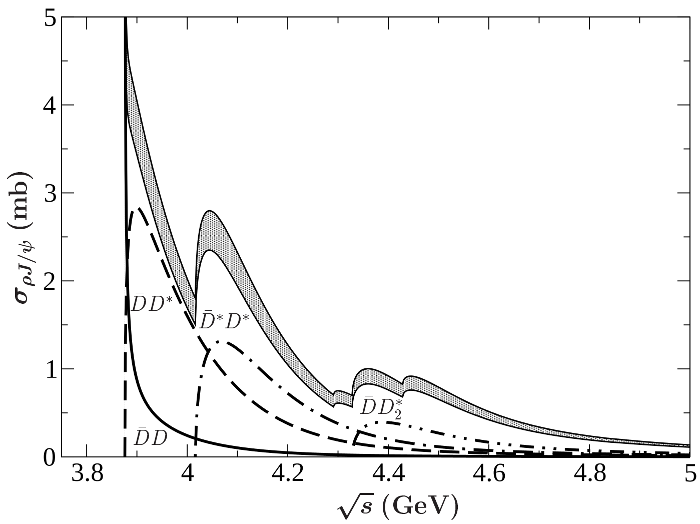

Figure 3. Same as in Fig. 2, but for $\rho J/\psi$ cross sections.

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